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SPECTRAL ANALYSIS OF EUV EMISSIONS FROM LANTHANIDE METAL ATOMIC IONS IN LARGE HELICAL DEVICE (LHD) PLASMAS (S31)

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To develop the shorter wavelength light source, we are suggested to investigate the heavier elements such as lanthanides. The wavelengths of the 4d - 4f transitions are reported to be, for example, 7.9 nm for Nd (Z=60), 7.0 nm for Eu (Z=63) , and 6.8 nm for Gd (Z=64) [1]. Recently, the 4d-4f transitions of Tb at 6.5 nm has been investigated theoretically by Sasaki et al [2].
Recently, emission spectra at around 6 – 7 nm range from Gd and Nd atomic ions have been measured using LHD (Large Helical Device) in NIFS (National Institute for Fusion Science, Japan). A Gd or Nd pellet has been injected into the plasma with the central electron temperature 2 ~ 3 keV, and the emission lines from Gd or Nd 4d open-shell ions has been observed.
Those lines have been analyzed and compared to the presently carried out atomic structure calculations. Theoretical calculation has been performed using a group of computer codes GRASP92 [3], RATIP [4], and GRASP2K [5].

References
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Measured EUV Spectra of Gd ions in LHD plasmas

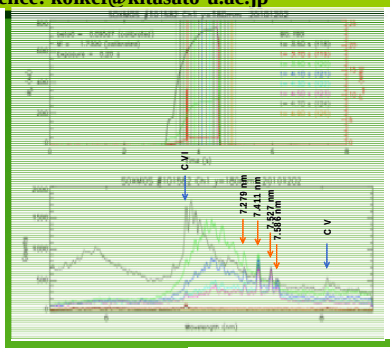
Gd (Z=64) EUV emission spectra from LHD plasmas. The Gd atoms are injected as a tracer into the LHD plasmas with 2~3 keV of the electron temperature.
Four discrete lines are also observed around 7.5 nm, which are suspected to be of the higher charge state Gd ions.

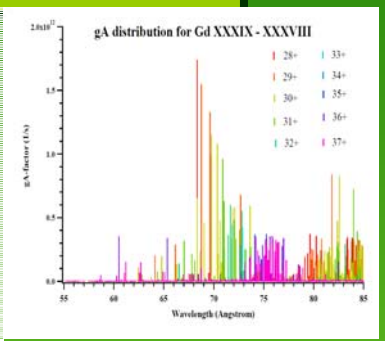
Upper entry: Time variation of stored energy (Wp, black curve) and radiation amount (Prad, red curve).

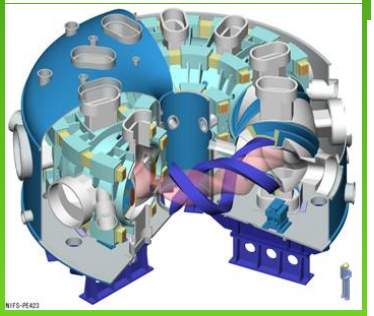
Lower entry: Time variation of the spectra around 7 nm measured by SOXMOS.
Red curve: just before the TESPEL injection of 3.8 s duration.
Green curve: 3.9 s,
Blue curve: 4.1 s,
Light blue curve: 4.3 s, and
Violet curve: 4.5 s after the start of TESPEL injection,
respectively.
Grey curve: 4.7 s, which is the time of plasma dislapstion.

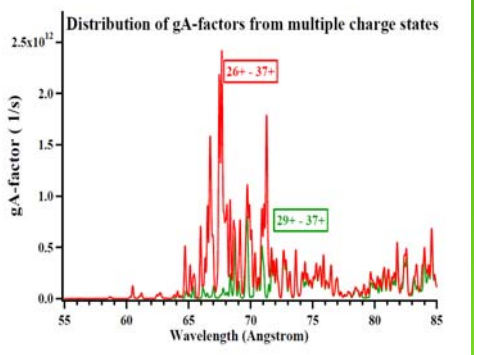
The spectral structures centered at 6.8 nm and 4 spectral lines at 7.279 to 7.586 nm are of Gd ions.

The spectral structures near 5.9 nm are inspected to be of W



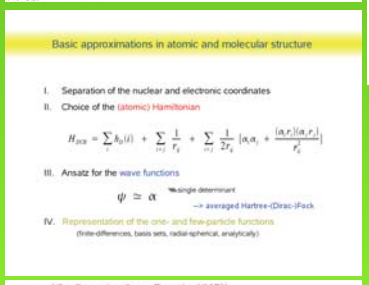


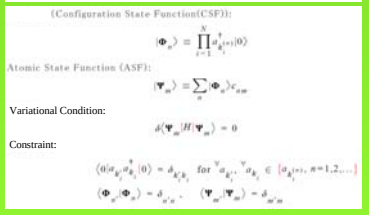




Newly Observed Lines and Calculated Lines of Gd Ions

Ionic Charge	Wavelength (nm) Present Experimen	Hullac Calculation	GRASP Calculation	Values in the literature	Transition Upper State	Lower State
28+			6.834		$3d^{10}4s^24p\text{-}4p^44d\text{-}$ J=1	$3d^{10}4s^24p\text{-}^24p^4$ J=0
29+			6.875		$3d^{10}4s^24p\text{-}4p^34d\text{-}$ J=5/2	$3d^{10}4s^24p\text{-}^24p^3$ J=3/2
30+			6.976		$3d^{10}4s^24p\text{-}4p^24d\text{-}$ J=3	$3d^{10}4s^24p\text{-}^24p^2$ J=2
31+			7.097		$3d^{10}4s^24p\text{-}4p4d\text{-}$ J=1/2	$3d^{10}4s^24p\text{-}^24p$ J=3/2
31+			7.103		$3d^{10}4s^24p^24d\text{-}$ J=7/2	$3d^{10}4s^24p\text{-}4p^2$ J=5/2
32+			7.168		$3d^{10}4s^24p\text{-}4d\text{-}$ J=1	$3d^{10}4s^24p^2$ J=0
33+	7.279	7.279	7.288		$3d^{10}4s^24d\ ^3D_{3/2}$	$3d^{10}4s^24p\ ^2P_{1/2}$
34+	7.406	7.406	7.411		$3d^{10}4s4d\ ^3D_2$	$3d^{10}4s4p\ ^3P_1$
35+	7.527	7.522	7.528	7.532	$3d^{10}4d\ ^2D_{3/2}$	$3d^{10}4p\ ^2P_{3/2}$
36+	7.586		7.586		$3d^94d\ ^3F_4$	$3d^94p\ ^3D_3$
37+			7.650		$3d\text{-}^23d^94d\text{-}$ J=1/2	$3d\text{-}^23d^94p\text{-}$ J=3/2





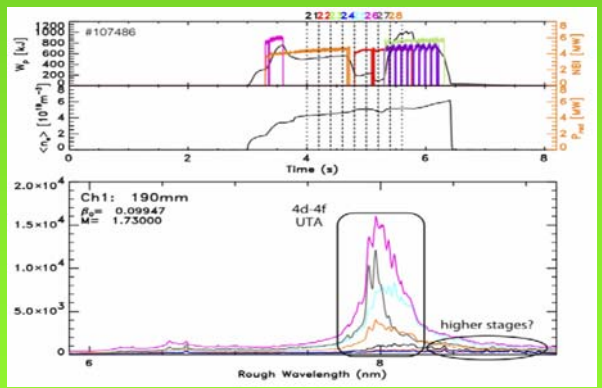
Measured EUV Spectra of Nd ions in LHD plasmas

Nd (Z=60) EUV emission spectra from LHD plasmas. The Nd atoms are injected as a tracer into the LHD plasmas with 2~3 keV of the electron temperature.
Several line spectrum from higher charge state ions are observed in the range 8.4 to 9.0 nm.
4d-4f and 4p-4d transition arrays are observed at ~7.9 nm, which are at slightly longer wavelength range compared to the spectrum from the lower temperature plasmas.

Upper entry: Time variation of stored energy (Wp, black curve) and radiation amount (Prad, red curve).

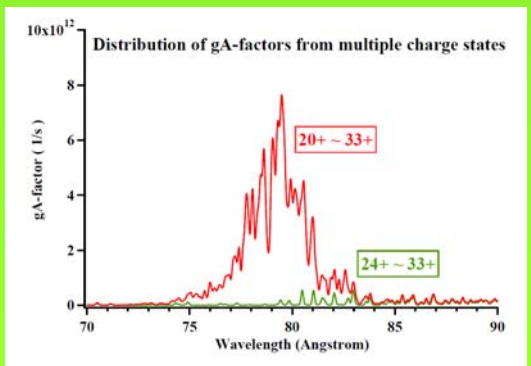
Lower entry: Time variation of the spectra around 8 nm measured by SOXMOS.

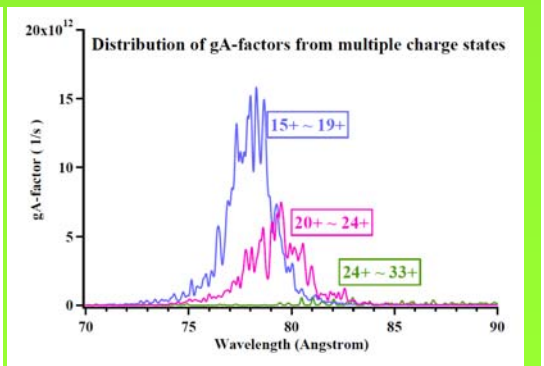
The colors of the spectral profiles indicate the time points when the measurements are carried out.



Atomic Code:

1. **GRASP92 (General purpose Relativistic Atomic Structure Program 92)**
2. **RATIP (Relativistic Atomic Transition and Ionization Properties)**
3. **GRASP2K (General purpose Relativistic Atomic Structure Program 2K)**





Summary:

1. **Photoemissions of Gd ions have been observed.**
   a. **4d-4f transition arrays have been observed at 6.8 nm.**
   b. **4 discrete lines at 7.729 to 7.586 nm have been observed.**
2. **Photoemissions of Nd ions have been observed.**
   a. **4d-4f transition arrays have been observed at 7.9 nm**
3. **Precise theoretical atomic structure calculations have been carried out to identify the observed lines.**
4. **Further extensive experimental work are desired for Gd and Nd ions.**
5. **The extension of the experiments to the species such as Tb is to be planned.**